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*Published in:*
Danish Journal of Transportation Research - Dansk tidskrift for transportforskning

*Publication date:*
2012

*Document Version*
Publisher's PDF, also known as Version of record

Denne artikel er publiceret i det elektroniske tidsskrift
**Udvalgte artikler fra Trafikdage på Aalborg Universitet**
(Selected Proceedings from the Annual Transport Conference at Aalborg University)
ISSN 1903-1092
www.trafikdage.dk/artikelarkiv
Modtaget 01.10.2012
Godkendt 06.12.2013

# Implementation of Bus Rapid Transit in Copenhagen: A Mesoscopic Model Approach

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## Abstract

Bus Rapid Transit (BRT) has shown to be an efficient and cost-effective mode of public transport, and has gained popularity in many cities around the world. To optimise the operations and infrastructure it is advantageous to deploy transport models. However, microscopic models are very inefficient for large scale corridors due to the vast amount of data and resources required. Hence, it is relevant to investigate how to model and evaluate BRT efficiently.

In this paper the effects of implementing BRT in Copenhagen is discussed including how to evaluate and model bus operations. For this purpose, a mesoscopic simulation model is developed. In the model bus operations are modelled on a microscopic level whereas the interactions with other traffic are modelled macroscopically. This makes it possible to model high-frequency bus services such as BRT lines in more details without the time consumption of micro-simulation models. The developed model is capable of modelling bus operations in terms of travel time and reliability including important mode-specific issues such as bus bunching.

The model is applied to a BRT project proposal with different combinations of BRT elements. The model results show that infrastructure upgrades (busways and enhanced stations) ensure a reduction to travel time whereas no improvements to reliability occur. Upgrades to technology and service planning (pre-paid fare collection, boarding and alighting from all doors, special BRT vehicles, ITS, and active bus control) ensure an increase in service reliability whereas only small reductions to travel time are observed. By combining all BRT elements it is possible to obtain synergies where the improved reliability due to planning and technology elements makes it possible to utilise the infrastructure optimally. Hence, it is possible to increase commercial speed from 14.8 to 19.9 km/h and service reliability in terms of headway time regularity from 46% to 84% aggregated on both directions for the morning peak period making the implementation of BRT feasible from a pure financial point of view.

# 1 Introduction

An efficient and attractive public transport system should provide high commercial speed,  high-frequency operations, user comfort, and a predictable service. In the congested city high running speeds can only be achieved in segregated infrastructure, user comfort requires high quality vehicles and stations, and predictable service needs control of, and protection against, external interference of the system. Such attributes are known from modern metro and light rail systems; for trains to run they need a specialised infrastructure, special vehicles, and a high level of control. In contrast, conventional bus services require nothing more than a basic vehicle to operate. Hence, conventional bus services are often subject to congestion, poor comfort, and a large degree of randomness. This is reflected in low travel speeds, less predictable service, thus a generally lower service quality.

Bus Rapid Transit (BRT) is a concept which combines the positive service elements from rail services with the low costs and high level of flexibility of buses. The main elements of BRT are segregated busways, enhanced stations, specialised vehicles, improved service planning, pre-board fare collection, a strong identity, and Intelligent Transport Systems (ITS) (Wright & Hook, 2007).

The amphibious nature of BRT using elements from both rail-based transit and bus-based transit makes BRT challenging to analyse. It is therefore relevant to develop a method that can model and assess the system in its elements efficiently. Traditionally microscopic models have been deployed, but they are time consuming for large scale corridors due to the vast amount of data and resources required. Therefore, this study aims at developing a mesoscopic model which is able to capture and assess both the different BRT elements individually and as a full BRT system. This includes a discussion of service reliability in order to propose a measure of how to evaluate reliability within high-frequency public transport systems such as BRT systems. The term BRT is used internationally to describe a large variety of bus systems ranging from systems with only few BRT elements installed to comprehensive systems that includes all features and hence are operating fully segregated from other traffic. As BRT can be implemented as a combination of different elements, it is furthermore relevant to study how the elements can be used to support each other. Hence, to test the model and evaluate the effects of introducing the elements of BRT individually and as a full system three BRT scenarios are analysed for a case study corridor in Copenhagen.

The remainder of this paper is structured as follows. In section 2 the characteristics of service reliability is discussed as this is crucial for the modelling and assessment of high-frequency bus operations. In section 3 the model developed as part of this study is introduced and described. In section 4 the case study corridor is introduced together with the three defined BRT scenarios, and the developed model is applied and validated on the base scenario. The effects of introducing BRT are presented in section 5. In section 6 the results are discussed, and section 7 concludes the findings.

The paper is a summary of the findings in the Master's thesis by the same authors at DTU Transport, hence more information can be found in (Ingvardson & Jensen, 2012).

# 2 Service reliability of high-frequency public transport

Service reliability is one of the important factors to cope with when managing public transport. Ultimately unreliable operations make it necessary for the users to add a buffer to the travel time thus extending the actual travel time (Ceder, 2007).

Reliability can be defined as "*continuity of correct service*" (Avizienis, Laprie, & Randell, 2000). This can be interpreted as maintaining the same service which from the passengers' point of view would be equal to a combination of experiencing the same waiting time at the departure stop, and experiencing the same in-vehicle travel time between departure stop and arrival stop independent of the departure time. For high-frequency public transport operations this implies a low level of variation in the running time, and maintaining a homogenous headway time between vehicles. In New York City reliability is measured by the *service regularity*. It is measured as the percentage of headway times that deviates less than 50% from the scheduled headway time for bus operations which have a scheduled headway time of less than 10 minutes (Nakanishi, 1997). By using this measure it is possible to evaluate to which degree vehicles arrive within the same headway time, and thus whether passengers experience a *reliable* service.

The reliability term can be described by distributions (Ceder, 2007). Hence it is possible to measure public transport attributes related to reliability in statistical terms. The mean, variation and coefficient of variation are therefore useful measures for the level of variation of the operation, e.g. the running time. These statistical indicators for assessing reliability are used in a number of recent BRT studies in Denmark, including (Viatrafik, 2012) and (City of Copenhagen, 2011). Furthermore, Balcombe, et al. (2004) argues that the lack of reliability can be quantified by the standard deviation multiplied by the corresponding value of in-vehicle or waiting time, hence supporting the use of statistical terms. Thus, the effective waiting time includes the mean waiting time and the standard deviation due to unreliability. This also suggests that the standard deviation of the headway times should be considered in the examination of quality of service for bus operations.

Hence, we propose to measure the service reliability of high-frequency BRT systems in a two-fold manner as sketched in Figure 1.

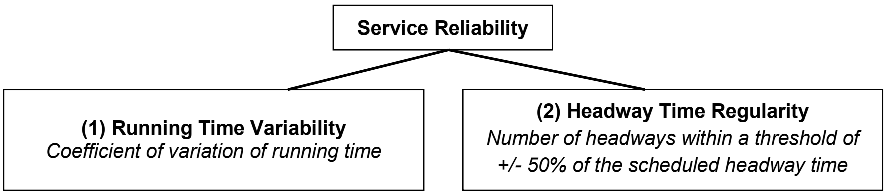


**Figure 1: Measures of service reliability for high frequency BRT operations as proposed by (Ingvardson & Jensen, 2012).**

The metrics applied in the evaluation of *service reliability* are: (1) the coefficient of variation of the running time (*running time variability*), and (2) the number of headway times within the threshold of +/- 50% of the scheduled headway time (*headway time regularity*). By this it is possible to capture the continuity of both running times and headway times. This ensures an indicative measure of the total travel time experienced by passengers on a given high-frequency public transport line.

## 2.1 The bus bunching problem

One of the most distinctive reliability phenomena in urban bus operations is the 'bus bunching' problem which has been the subject of much research in the past 50 years (Newell & Potts, 1964). The problem occurs because a small disturbance in the running time for one bus is magnified over time causing buses to pair up instead of maintaining a certain distance according to the headway time.

One of the main reasons for bus bunching is the variability of the time spent dwelling at stops. If for some reason the bus is delayed, the headway time to the bus in front will be increased. When the delayed bus arrives at the next stop more passengers will be boarding at this stop due to the longer headway time. This causes an additional delay for the already delayed bus. Simultaneously, the subsequent bus will catch up with the delayed bus decreasing the headway time, thus collecting fewer passengers at the stop. The effect will be further magnified if passengers arrive in clusters or if the boarding process is inefficient. The bunching problem is illustrated by Figure 2.

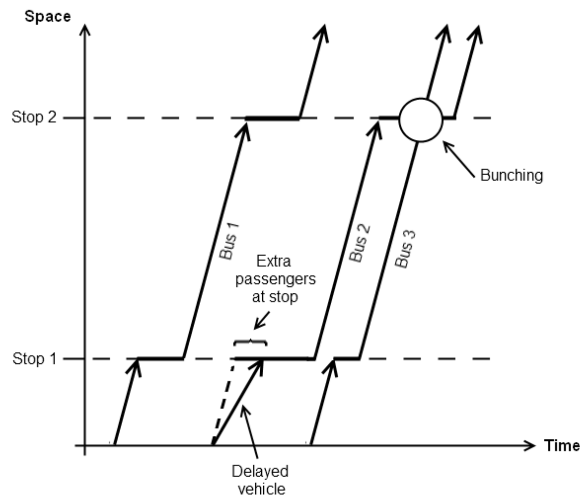


**Figure 2:** **The principle of bus bunching where buses catch up with one another due to variable dwell times at stops. Based on (Ceder, 2007).**

The problem of bus bunching not only causes delays for the passengers in the delayed bus, but also increases the waiting time for passengers waiting at the stops. For high frequency routes where passengers are assumed to arrive randomly Wilson, et al. (1992) references that the expected waiting time for passengers can be expressed by:

$$\bar{w} = \frac{\bar{h}}{2} \cdot \left(1 + \mathrm{cov}^2(h)\right)$$

where $\bar{w}$ is the average passenger waiting time, $\bar{h}$ is the mean headway time, and cov($h$) is the coefficient of variation of the headway time. This shows that if the variation in headway times is small the expected waiting time is half the headway time whereas the expected waiting time increases as the headway time variability increases.

Additionally, overcrowding will result in a low level of comfort, or even result in the need for the bus to pass the stop without collecting passengers. Hence, it may be the majority of passengers that experience low comfort and increased travel and waiting times even though only a few buses will be bunched.

# 3 Model approach

The evaluation of BRT on an existing corridor requires a simulation of the existing situation of conventional bus service, and a simulation of the situation after the implementation of BRT. This is a special task as the differences between BRT and conventional bus services are related to both the infrastructure and to the specific operation of buses. Consequently, the requirements to the model type will be a detailed micro-simulation of bus operations but taking into account the large scale of a project covering a relatively long corridor.

When evaluating traffic on an operational level micro simulation models are the preferred instrument (Cats, Burghout, Toledo, & Koutsopoulos, 2010). Also recent Danish BRT studies including (Viatrafik, 2012) and (City of Copenhagen, 2011) utilises micro simulation models as the main tool. However, due to the high level of detail preparation of input data for micro simulation models can be time-consuming. The time-consumption and complications related to micro-modelling increases with the size of the network making it inappropriate for larger networks, e.g. entire corridors (Cats, Burghout, Toledo, & Koutsopoulos, 2010).

In this paper we propose to model bus operations by developing a mesoscopic model approach which simulates the operation of buses individually in a detailed manner whereas other traffic is macroscopically determined using distributional data. This is in line with the approach proposed in (Meignan, Simonin, & Koukam, 2007) where vehicle types are distinguished depending on the purpose and context of the model.

By this, operation dynamics of large-scale public transport systems can be modelled in greater detail without the complications related to data and calibration of micro-models (Cats, Burghout, Toledo, & Koutsopoulos, 2010).

The operation of buses and their movements are simulated stepwise and independently based on observations of bus behaviour in Copenhagen and Istanbul conducted as part of (Ingvardson & Jensen, 2012). Hence, conventional bus operations are simulated by use of current observations from bus line 5A, whereas observations from Metrobús in Istanbul have been used to model a situation with BRT features in Copenhagen. By utilising this form of data in the model it is possible to simulate the variation in operations without data on exact traffic levels in roads and intersections (Ceder, 2007). An illustration of the overall work flow of the model is sketched in Figure 3.

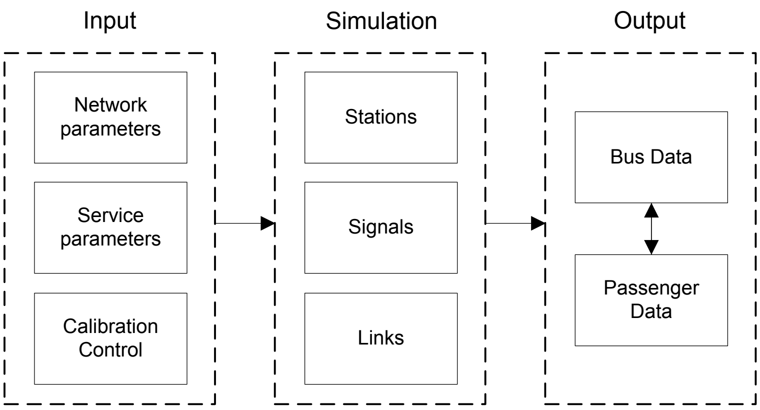


**Figure 3: Illustration of the model framework including input and output.**

## 3.1 Input

The input to the model consists of characteristics related to the network, the passengers, and the bus operation. The input values are based on empirical data collected as part of (Ingvardson & Jensen, 2012) and official data from (Movia, 2011) which is implemented in a stochastic manner as statistical distributions as proposed by (Ceder, 2007). Hence, it is possible to simulate the variation of bus operations based on the statistical variation in the input parameters such as passengers boarding a specific bus, and the speed of a specific bus on a specific link.

### 3.1.1 Network Parameters

The network consists of links, signals, and stations. These are associated with a number of parameters, e.g. for links this include the length and optimal speed whereas it for signals include the cycle time and green time.

### 3.1.2 Service Parameters

Service parameters are related to the level of service and the operation of buses. Hence, this includes the boarding and alighting time per passenger, and the vehicle seat capacity. The dispatching input includes the headway time between departures at the starting node and the level of randomness by which buses are dispatched, i.e. the level of bus bunching at the departure stop.

### 3.1.3 Calibration Controls

To capture minor variations of bus operations a number of calibration control parameters have been implemented. These parameters include holding controls, and reflect the behaviour of a driver who catches up with a bus and thus holds back to ensure a certain gap between the buses. This also makes it possible to simulate and evaluate bus bunching controls as part of the analyses.

## 3.2 Simulation

The simulation of buses is based on the characteristics of bus operations which suggest that the travel time of an individual bus basically consists of three elements: time spent to overcome distance, time spent dwelling at stops, and time spent waiting at signals. The time spent on links overcoming distance depends on the speed and acceleration profile of the vehicle and external factors such as congestion. Time spent at stops depend on a fixed amount of time for deceleration and acceleration and for opening and closing the doors. Additionally there is a variable amount of time used for passengers to board and alight the vehicle which is dependent on vehicle and service planning characteristics. The same is the case for signals along the route where the bus potentially uses a fixed amount of time to decelerate and accelerate and a variable amount of time for waiting at the signal. At each event for every bus the model will calculate the position, time and occupancy, e.g. when arriving at a stop these parameters are calculated based on the input variables.

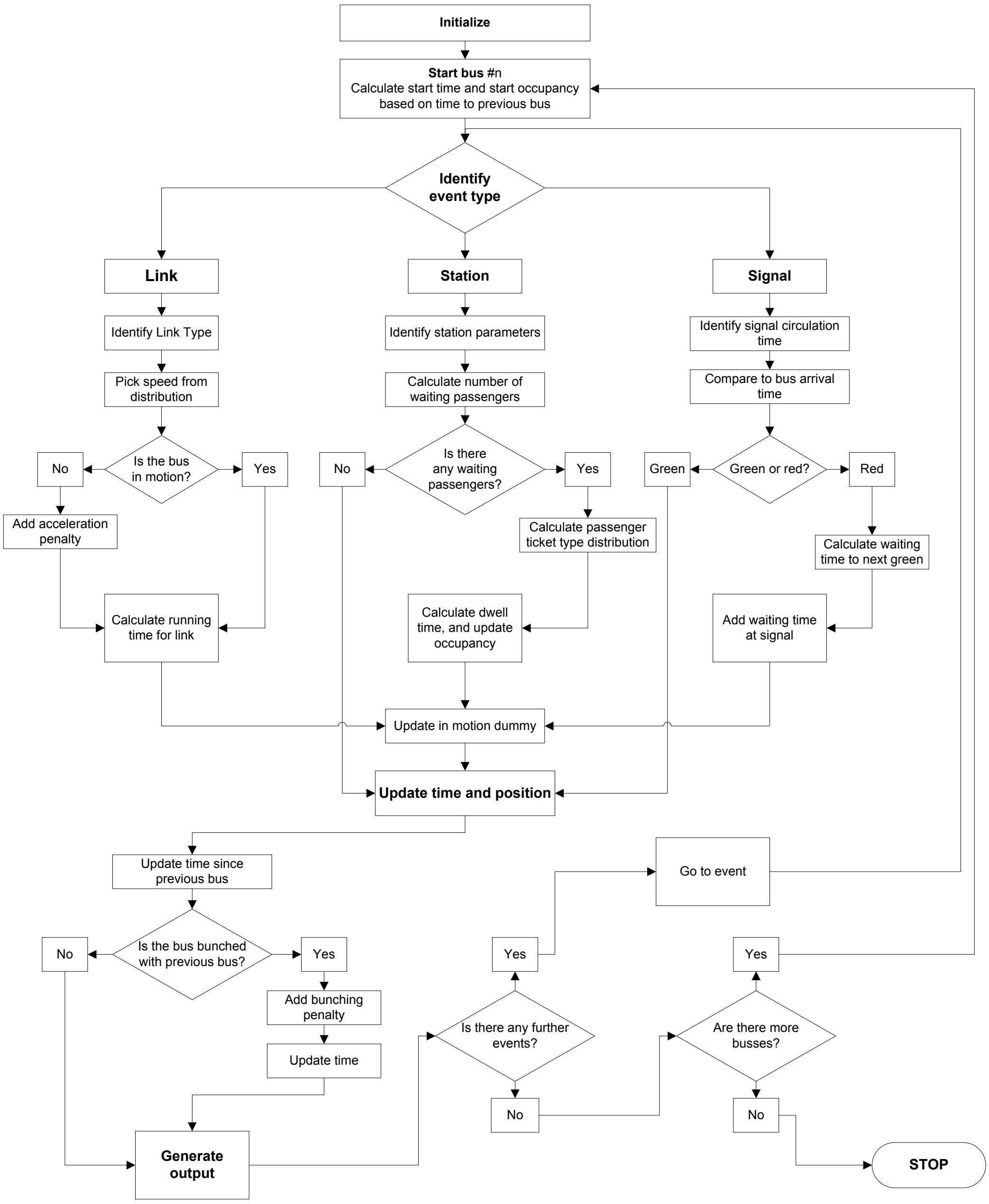


**Figure 4:** **Detailed overview of the model simulation framework. More information can be found in (Ingvardson & Jensen, 2012).**

After initialising the model with relevant input the first bus is assigned. The bus initially identifies the first event. Then the time, distance travelled, and changes in occupancy at the event are calculated. The output from the event is an update of this information (time, location, and occupancy) which is used as input to the next event. At every event the bus calculates the time to the bus in front which is used in the calculation of number of passengers waiting at stops and to control bunching. At the same time a dummy variable denoting whether the bus is in motion or not is updated. This dummy is implemented as the travel time on a link is dependent on whether the bus is already in motion or needs to accelerate. When all buses have been through all events, i.e. travelled the entire corridor, it is possible to calculate and evaluate the effects for buses and passengers.

### 3.2.1 Links

The time spent by the bus travelling on links generally depends on trip time (e.g. hour, day, week, season), number of passengers, and the habits of the individual driver (Ceder, 2007). On individual links the travel time can be estimated according to traffic flow theory (Ortúzar & Willumsen, 2001). As the model only includes buses and not car traffic this model estimates the speed of the bus on a given link.

The framework for calculating the speed of buses is based on letting the speed of the bus be randomly distributed thus simulating that the travel speed of buses both depend on local conditions of the road and on external factors such as driving behaviour. Hence, when a given bus arrives at a given link the speed on that link will be randomly drawn from an appropriate link-specific distribution. In this way it is possible for the model to calculate the time it takes for the bus to travel on that link. To include the fact that the characteristics of the road influence the speed of the bus the links in the network has been categorised into different link types, see Table 1.

| Link Type | Description | Distribution | Mean [km/h] | Standard Deviation [km/h] | Comment |
|---|---|---|---|---|---|
| W | No disturbance from other traffic. This includes busways only. | Normal | 60.5 | 4.85 | |
| N | Low disturbance from other traffic. This includes bus lanes. | Normal | 37.4 | 3.60 | |
| M | Medium disturbance from other traffic. This includes mixed use lanes. | Normal | 26.0 | 3.18 | |
| K | High disturbance from other traffic. This includes road with some congestion. | Normal | 17.9 | 1.91 | |
| H | Very high disturbance from other traffic. This includes roads with major congestion. | Normal | 9.8 | 3.06 | Can only take on values in the interval [5,15] |
| E | Narrow roads. Low disturbance from other traffic, but bus is limited to run at low speeds. | Normal | 20.0 | 2.70 | |

**Table 1: List of linktypes used in the model.**

The categorisation is based on both the travel speed and the traffic congestion level which is defined based on the actual speed, $v$, and the free speed of the link, $v_f$, as $(1 - v/v_f)$. Both measures are included to take into account the variability of travel speed as this to a large extent depends on the congestion level. The congestion level on roads is based on output from a road traffic assignment model covering Copenhagen[1] whereas the distribution of travel speeds for such roads, i.e. mean and standard deviation, is based on empirical data from (Ingvardson & Jensen, 2012).

[1] The model is based on OD-matrices from OTM version 4, and the assignment model Traffic Analyst used at DTU Transport.

Each linktype has been assigned a number of parameters which makes it possible to calculate the travel time for the bus on a given link. These parameters include the mean and standard deviation of the top speed on the link in addition to a penalty term which takes into account the acceleration of the bus. The latter is only included if the bus has been brought to a stop at the previous event such as at a red signal.

To justify the assumption that the empirical data are random and may be approximated by a distribution the data is tested using the Kolmogorov-Smirnov goodness of fit test (Johnson, 2005). The test results all show that the assumption of a normal distribution cannot be rejected at neither a 95% nor 80% level of confidence. Thus, the normal distribution is accepted as providing a good fit for the data.

Due to the nature of the normal distribution which is symmetric around the mean it has been necessary to limit the possible values for links of type H, cf. Table 1. The speed on these links can only take on values between 5 and 15 km/h. This has been done to avoid very low or even negative speeds in the model.

### 3.2.2 Signals

Signals are simulated as nodes and are defined by three input parameters: a cycle time, a green start time, and a green end time. From this the potential waiting time for a given bus approaching a signal until the next green is calculated. The input parameters are adapted from the current signal timing plans (City of Copenhagen, 2012). Signals that currently have bus priority implemented are simulated using the extended green time, and delays caused by other traffic have been implemented by use of a time penalty, e.g. when turning left crossing opposing traffic.

### 3.2.3 Stations

Stations are modelled like nodes with two parallel procedures being calculated simultaneously; the number of boarding passengers, and the number of alighting passengers. These are used to calculate the total dwell time for the bus.

The dwell time depending on the number of boarding and alighting passengers when boarding and alighting through the same door can be estimated by a linear model of the form (Ceder, 2007):

$$D_{ik} = \begin{cases} b + \delta_B \cdot B_{ik} + \delta_A \cdot A_{ik} & , if\ B_{ik} > 0\ or\ A_{ik} > 0 \\ 0 & , if\ B_{ik} = A_{ik} = 0 \end{cases}$$

For buses with multiple doors where boarding and alighting passengers use different doors the dwell time can be calculated as (Ceder, 2007):

$$D_{ik} = \begin{cases} b + \max(\delta_B \cdot B_{ik} + \delta_A \cdot A_{ik}) & , if\ B_{ik} > 0\ or\ A_{ik} > 0 \\ 0 & , if\ B_{ik} = A_{ik} = 0 \end{cases}$$

| | |
|---|---|
| $D_{ik}$ | Dwell time of the vehicle serving trip *i* at stop *k* including the time required for acceleration and deceleration ($D_{ik}$ = 0 if the bus do not stop at *k*) |
| $b$ | Dead time portion including acceleration, deceleration, and closing and opening of doors. |
| $B_{ik}$ | Number of passenger boarding the vehicle serving trip *i* at stop *k* |
| $A_{ik}$ | Number of passenger alighting the vehicle serving trip *i* at stop *k*. |
| $\delta_B$ | Marginal dwell time per boarding passenger |
| $\delta_A$ | Marginal dwell time per alighting passenger |

This model suggests that the total dwell time for a bus can be estimated by a fixed time including acceleration and deceleration, and opening and closing of doors, and a variable time depending on the number of passengers boarding and alighting the vehicle. If the bus has separate doors for boarding and alighting passengers these events happen independently of each other, and the variable term of the dwell time then depend on the event which takes the longest time. However, if the bus has only one door, or the doors are used for both boarding and alighting, the events cannot happen simultaneously. For BRT the latter will to some extent be the case as the doors are used by both boarding and alighting passengers hence creating conflicts.

The number of boarding passengers at a bus stop, i.e. passengers arriving at a bus stop, is assumed to be random as the buses run at a high frequency with headway times less than 10 minutes (Nakanishi, 1997). Hence, the arrival intensity is assumed to follow the Poisson distribution similar to in (Cats, Burghout, Toledo, & Koutsopoulos, 2010). From this it follows that the time between passenger arrivals, the passenger headway time, is exponentially distributed (Johnson, 2005). Hence, the number of boarding passengers at a given departure at a given stop can be calculated based on the mean passenger arrival intensity for that given stop. The number of alighting passengers in the bus is calculated based on the occupancy in the bus at the given stop and the share of passengers alighting at that stop in the given time period.

## 3.3 Output

The output of the model consists of the time, position, and occupancy for all modelled buses at all events. This can then be used to evaluate level of service parameters such as waiting times at stops, travel time for buses and passengers, and headway time distributions. By this it is possible to evaluate the operation including the experienced service reliability as experienced by passengers, and to compare the effects obtained by implementing various BRT elements.

# 4 Case Study Corridor

The selected case study corridor is part of the busiest bus line in the Copenhagen area, 5A, which runs between Husum Torv and Sundbyvester Plads (Movia, 2011). In this paper the section between Nørreport station and Sundbyvester Plads is analysed. This segment is 6.5 km long and currently covers 18/19 stops in the southbound/northbound direction respectively. An overview of the segment can be seen in Figure 5.


Figure 5: The 5A corridor between Nørreport station in central Copenhagen and Sundbyvester Plads on Amager.

The current corridor has several BRT elements implemented including a high frequency, a special identity, and dedicated bus lanes on 44%/37% of the corridor for the southbound/northbound direction respectively. Despite these elements the operation suffers from low reliability and slow travel speeds (Ingvardson & Jensen, 2012).

## 4.1 Model Replication

The validation of whether the simulated model results accurately replicate the real world has been done by comparing the model results to real-life as proposed by (Abdelfattah & Khan, 1998). According to (Cats, Burghout, Toledo, & Koutsopoulos, 2010) this can be done by a two-sample Kolmogorov-Smirnov test. The parameter that is being tested is the headway time distribution of buses at Amagerbro station in both directions, and at Nørreport station in the northbound direction as data were only available for these locations. The test statistics are shown in Table 2.

| Test parameters | D | KSa | Pr > KSa |
|---|---|---|---|
| Amagerbro st Southbound | 0.1197 | 0.7998 | 0.5444 |
| Amagerbro st Northbound | 0.1004 | 0.6630 | 0.7715 |
| Nørreport st Northbound | 0.0869 | 0.5944 | 0.8716 |

**Table 2:** **The Kolmogorov-Smirnov test statistics for the null hypothesis that the distributions of the simulated and observed headway times are identical.**

The null hypothesis is that the distributions of the modelled and simulated headway times are identical. Hence, that the modelled headway times are a replication of the headway times experienced in real life. Based on the probability values the null hypothesis cannot be rejected at a 95% level of confidence. Hence, the model replicates reality with regards to headway time distributions in an acceptable manner.

Optimally this validation method should be used for all relevant parameters in the validation process. However, the observed data on running times and time use shares do only include mean values from the buses and not distributional data. Hence, it is not possible to validate the model in this manner with regards to running time and time use shares. Instead the validation of these parameters is done by use of mean and standard deviation values. The main validation results are shown in Table 3.

| Northbound | Average running time | Running time variability | Commercial speed [km/h] | Headway time regularity |
|---|---|---|---|---|
| Observed base | 28 min 22 sec | 8.9% | 13.6 | 48% |
| Modelled base | 28 min 27 sec | 6.4% | 13.6 | 47% |

| Southbound | Average running time | Running time variability | Commercial speed [km/h] | Headway time regularity |
|---|---|---|---|---|
| Observed base | 24 min 23 sec | 6.1% | 16.0 | 51% |
| Modelled base | 24 min 30 sec | 5.5% | 16.0 | 44% |

**Table 3:** **Model simulation results[3] for the base situation compared to the real base situation.**

The headway time regularity is measured as +/- 50% of the scheduled headway time. The shown value is the average at Amagerbro station and Nørreport station as these are the only stations where observed data is available. Optimally it should be an average of all stations on the route. The comparison shows that the model replicates reality well with regards to travel time as the model and observed average values are almost identical. However, the modelled service reliability measures are lower than the observed values. Hence, it seems that the model has difficulties simulating large reliability problems.

The average running times for buses is shown in the time-space diagram in Figure 6.

[3] Model results are for a typical morning peak period (7-9) including 72 buses (18 per hour per direction), and are averages of 50 runs.

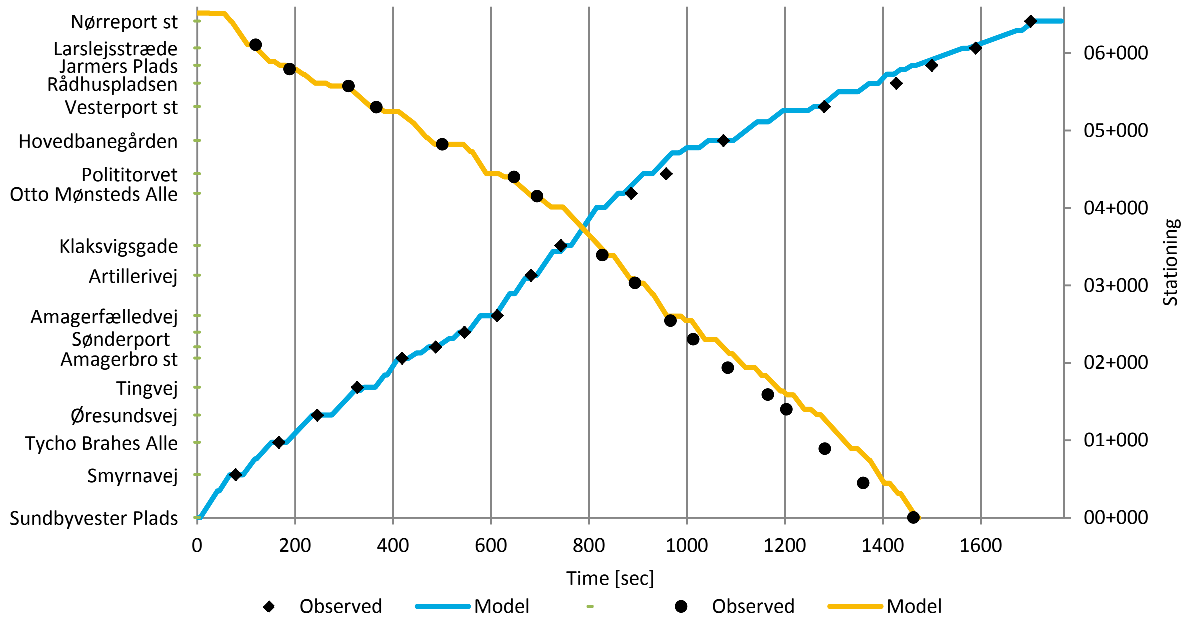


**Figure 6:** Representation of average running times for all buses in the model simulation.

The model estimates of the travel time between stops seem to reflect the observed values in an acceptable manner. That is, the variation between the observed and model estimates of accumulated times at stops are less than one minute for all stops.

## 4.2 Scenarios

The model is applied to analyse the effects of upgrading the current 5A bus line in Copenhagen to BRT standards. As BRT can be implemented on various levels it is relevant to investigate the effects of the different BRT elements individually, and combined. For this purpose three scenarios have been set up. This is outlined in Table 4.

| Infrastructure only | Technology and service planning only | BRT |
|---|---|---|
| Infrastructure is upgraded, but the vehicles and ticketing system remain unchanged. | Service planning and technology is optimised to BRT standards. The infrastructure remains unchanged. | Infrastructure, service planning and technology are upgraded to BRT standards. |

**Table 4:** Overview of the performed analyses of upgrading bus line 5A to BRT standards.

For the infrastructure only scenario segregated busways are applied on segments where possible while ensuring that existing traffic is not influenced significantly. Hence, we propose to upgrade the corridor so that a total of 2.9 km segregated busways and 1.2 km bus lanes are implemented along the 6.5 km corridor. In addition, a new shorter alignment between Rådhuspladsen and Hovedbanegården is proposed as this makes it possible to implement segregated busways on a longer section of the corridor. The station spacing is optimised by maximising the generalised travel costs; hence the number of stations is reduced from 19 to 15. This results in an average station spacing of 430 meters. An overview of the upgraded infrastructure is shown in Figure 7.


**Figure 7:** **The layout of the proposed BRT upgrade of the 5A corridor between Nørreport station and Sundbyvester Plads.**

The technology and service planning scenario only includes upgrades to the vehicle fleet and the operation of vehicles. The buses are upgraded to articulated buses with four double-doors, and pre-board fare collection is implemented. Articulated buses ensure higher capacity, and the double-doors allow for faster exchange of boarding and alighting of passengers. Pre-board fare collection allows faster and more homogeneous passenger boarding times. Furthermore, a dynamic holding strategy is implemented in order to prevent bus bunching. The investigated holding strategy delays a bus by 5 seconds at a bus stop if the headway time to the bus in front is less than 120 seconds. No changes are made to the infrastructure, hence the buses uses the current infrastructure and station layout.

# 5 Results

The main results of the different scenarios with regards to travel time through the corridor are illustrated in Figure 8 for the morning peak period (7-9).

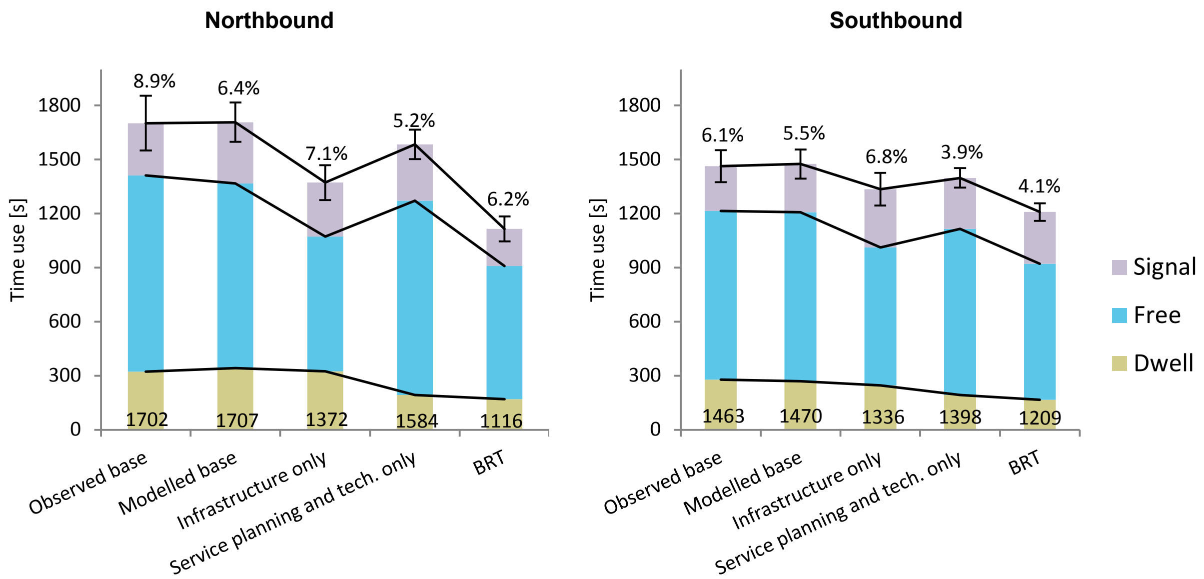


**Figure 8:** **Time use analysis and running time variability for the morning peak period for the three BRT scenarios. The graphs show the time use in seconds, and the running time variability as a percentage of the total running time.**

The infrastructure upgrades result in reduced running times whereas the dwell times are reduced when applying improvements to service planning. In the full BRT scenario both improvements are obtained. The running time variability is reduced by 25% when implementing full BRT, most significantly in the southbound direction. Furthermore, the results indicate that synergies appear when implementing an extensive BRT solution, see Figure 9.

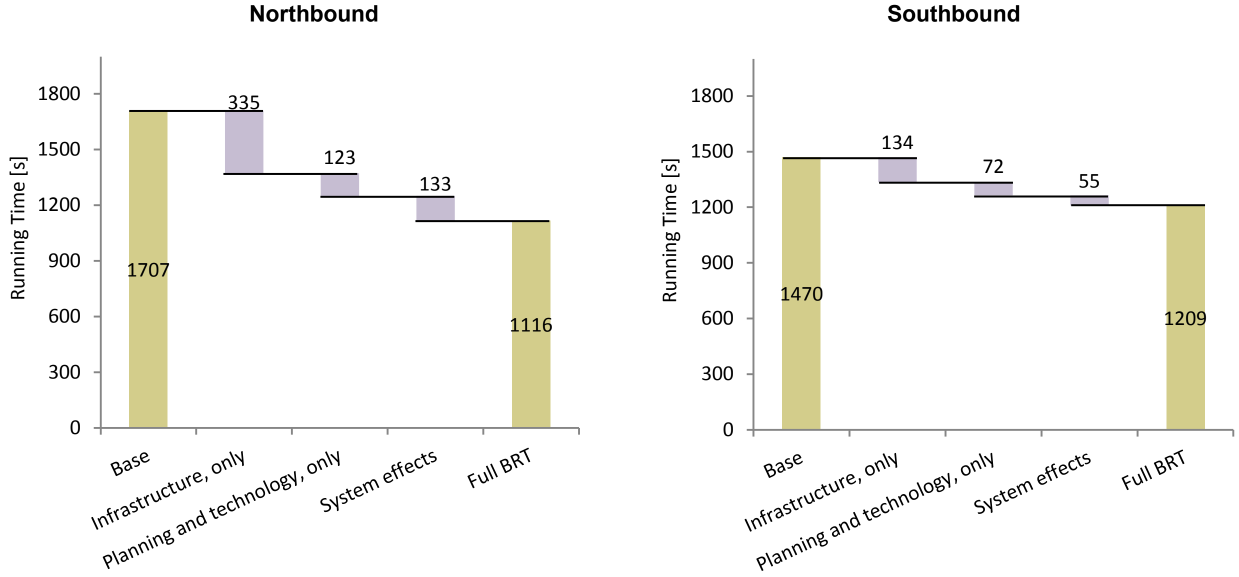


Figure 9: Travel time reductions for the morning peak period for the three BRT scenarios.

The travel time reduction in the full BRT scenario is larger than the sum of the reductions obtained by adding infrastructure elements, or only improving the service planning. This indicates the synergies obtained when combining the BRT elements into a coherent project. As the dwell times and running times become more predictable larger synergies can be obtained by adjusting the signals more efficiently.

The comparison of the improvements to the headway time regularity can be seen from Figure 10.

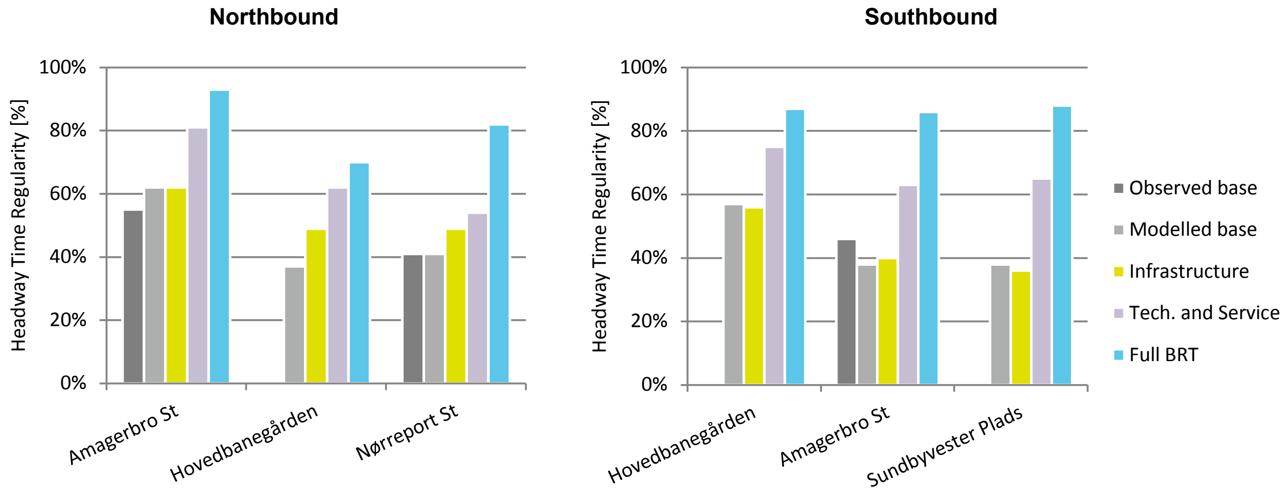


Figure 10: Headway time regularity on selected stations during the morning peak period for the three scenarios.

In all analyses the headway time regularity is improved. In the base situation the headway time regularity declines as buses move through the corridor, e.g. in the northbound direction the headway time regularity is 60% in the beginning of the corridor at Amagerbro station, and reduced to 40% at the end of the corridor at Nørreport station. This trend is reduced when upgrading the infrastructure or changing the service planning, and almost eliminated in the full BRT scenario. The headway time regularity is thus improved from 47% in the base situation to 84% in the full BRT scenario aggregated for both directions. This result indicates that improvements are achieved as a combination of the different BRT elements, rather than the result of one distinctive change. This can be seen from Figure 11.

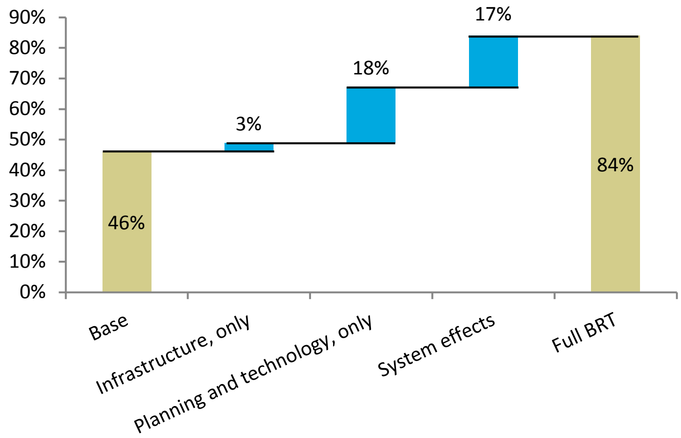


**Figure 11:** **Comparison of the improved headway time regularity for the morning peak period for the different analyses.**

The infrastructure improvements alone do not improve the headway time regularity since the key driver for bus bunching is the dwell time. It is therefore not possible to achieve a high headway time regularity by changing infrastructure only. Instead it is important to consider the dwell procedures and/or bunching controls. Where bunching control in terms of dynamic holding strategies increases the running time, all else equal, changes to the dwell procedures have positive effects for both running time and service reliability. The more efficient boarding and alighting procedure and bunching controls ensure an increase in headway time regularity of 18 percentage points which is further increased if also implementing infrastructure improvements due to the more efficient use of the infrastructure.

## 5.1 Financial analysis

The 6.5 km infrastructure upgrade is expected to cost approximately 350 million DKK (Ingvardson & Jensen, 2012). If implementing infrastructure elements only the project is not feasible due to limited benefits and large construction costs. By only implementing technology and planning elements it is possible to transform the current yearly deficit of 5A to a marginal profit. Hence, this is marginally feasible due to the assumedly low costs of implementation. However, if implementing a full BRT solution the increased ticket revenue due to the increase in number of passengers and the decrease in operating costs make the project financially viable with an estimated payback time of 13 years. (Ingvardson & Jensen, 2012)

# 6 Discussion

Bus rapid transit holds many opportunities in improving public transport systems of intermediate and developed cities. However, its benefits are limited by its application; a system which consists of expensive infrastructure may not yield the anticipated effects. For BRT to be successful it requires intelligent service planning and active use of the technology available. The same flexibility that makes BRT a cost efficient alternative to its rail-based counterparts poses a threat to the efficiency of the concept. However, if planned efficiently large effects can be obtained.

The mesoscopic approach proposed in this study makes it possible to simulate the elements of bus operations in detail while modelling less important elements on a macro-scale. The proposed approach makes it possible to evaluate the effects detailed as opposed to a macro assignment model, and without the need for large datasets and time-demanding model preparation as opposed to micro-simulation models. Hence, the mesoscopic model makes it possible to assess a public transport project in more details without the time consumption of micro-simulation models.

The proposed simulation model has been developed continuously and with a specific case in mind. This has put restrictions on the model as the data has been collected within the scope of the model and the case corridor. Hence, for the model to be adaptable to a general project, further research is required. The model approach does however seem promising. Due to the vast amount of data, which today is automatically collected via ITS, it seems appropriate to use distributions to describe bus operations instead of modelling all external elements individually, e.g. car vehicles. This has been seen to correctly represent current bus operations. This also makes the model appropriate as a simple tool for estimating BRT on other specific corridors.

The results of the case study in Copenhagen showed that a full BRT system can achieve large effects, both with regards to travel time and service reliability. The improved reliability is mainly achieved through the implementation of elements that streamline the boarding process as long and varying dwell times are seen to be destructive for maintaining a reliable service. Most systems in Europe seem to focus mainly on elements that decrease the travel time, e.g. bus lanes. However, as this study shows the effects of the system can be significantly improved if implementing a full BRT system.

The effects of the decreased travel time and increased reliability will most likely result in a higher number of passengers which will put pressure on the system. Due to the efficient boarding process with pre-board fare collection and vehicles with multiple doors the number of passengers does not influence the dwell time as much as seen in conventional bus operations. Hence, it is believed that the results can be obtained even if the number of passengers increases significantly. However, a detailed analysis of this challenge has not been performed as it is outside the scope of this study.

These analyses mainly focus on the passenger effects such as comfort, running time, and reliability measures. The benefits achieved by implementing BRT can however also be realised as savings on operating costs. It is possible to lower the frequency and still obtain better service reliability and running time savings, hence maintain the current level of service for passengers. Hence, the effects obtained by the more efficient bus operations can be allotted to either the passengers or the operator/transport agency, or it can be split between them.

# 7 Conclusion

When assessing high-frequency public transport systems from the passengers' point of view it is important to also consider service reliability. Based on the discussion of reliability in this study, we propose a joint measure of reliability which consists of evaluating both the headway times and the running times. More specifically, the service reliability measure is proposed to include i) the coefficient of variation of the running time, and ii) the number of headway times that are within +/- 50% of the scheduled headway time. This makes it possible to evaluate the quality of service in bus operations in a systematic manner as known from railways. In addition, by implementing a service reliability measure it will be possible for the transport agency to incentivise the operators to deliver a reliable service.

The mesoscopic model approach proposed in this paper makes it possible to simulate bus operations including the diversity of BRT elements individually. Hence, the mesoscopic model is applicable when assessing a public transport project in more details without the time consumption of micro-simulation models. Notable features of the model include the possibility to assess different holding control strategies for reducing bus bunching and a detailed modelling of dwell times.

The simulation of implementing BRT on bus line 5A in Copenhagen shows large increases to both travel time and service reliability, most significantly in the direction of the commute. When implementing upgrades to the infrastructure the travel time through the corridor decreases by 8-29% depending on direction whereas practically no improvements to service reliability occur. When implementing BRT elements related to technology and planning the service reliability in terms of headway time regularity is improved from 46% to 64% whereas only small improvements to travel time are observed. However, by combining all BRT elements it is possible to obtain synergies where the improved reliability due to planning and technology elements makes it possible to utilise the infrastructure more efficiently. Based on the model simulations the commercial speed in the corridor is increased from 14.8 to 19.9 km/t and the headway time regularity increases from 46% to 84%, aggregated on both directions in the morning peak period. These results indicate that it is important to not only consider infrastructure elements such as bus lanes when improving bus-based public transport. It is important to also consider elements which can ensure an efficient boarding and alighting process as well as holding strategies to reduce bus bunching. By this, the case study shows that it is possible to improve travel time and service reliability significantly resulting in an increase in number of passengers and decrease in operating costs. Hence, the case study project is economically feasible with a financial payback time of 13 years.

# 8 Acknowledgements

The authors would like to thank DTU Transport for making it possible to conduct this study, and especially our supervisor Associate Professor Alex Landex for helpful guidance during the project work.

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